An Axisymmetric, Radiative Bow Shock Model with a Realistic Treatment of Ionization and Cooling

Alejandro C. Raga[1], Garrelt Mellema[2] and Peter Lundqvist[3]

ABSTRACT

We have chosen a reduced set of 18 ionization rate equations (for ions of H, C, N, O, S and Ne), which allow us to obtain a moderately accurate estimate of the non-equilibrium radiative cooling function. We evaluate the accuracy of this approach by comparing our cooling function with previous calculations, computed with a more extended set of ions, for the case of gas that cools from a high temperature at constant density. We also compute steady, plane shock models, which we find to compare well with models calculated with much more detailed microphysics.

Using our reduced set of rate equations, we present a simulation of a radiative bow shock formed by a supersonic, plane stream impinging on a rigid sphere. The parameters for the calculation are chosen as to approximately represent typical values found for Herbig-Haro objects, and to give a cooling distance to bow shock radius ratio of 1/10. This simulation is done with an adaptive grid code, which allows a reasonably high resolution (with ≥ 25 points) of the standoff distance between the bow shock and the rigid obstacle.

Contrary to the standard expectation, we find that the bow shock standoff distance in the stagnation region is considerably shorter than the cooling distance behind a plane-parallel shock. Also, the centrifugal pressure is found to play an important role in determining the structure of the recombination region. This appears to partially invalidate previous bow shock models based on a "quasi-1D" approach, at least for the particular parameters chosen for the present simulation.

Finally, we present tabulations of the cooling rates that have been used (for the different species), in order to facilitate the inclusion of this treatment in other gasdynamic codes.

---

[1]Instituto de Astronomía, UNAM, Ap. Postal 70-264, 04510 México, D. F., México. E-mail: raga@astroscu.unam.mx

[2]Stockholm Observatory, S-133 36 Saltsjöbaden, Sweden. E-mail: garrelt@astro.su.se

[3]Stockholm Observatory, S-133 36 Saltsjöbaden, Sweden. E-mail: peter@astro.su.se

Subject headings: shock waves – numerical models – atomic data – Herbig-Haro Objects

1. Introduction

Both axisymmetric and three-dimensional (3D) numerical simulations of Herbig-Haro (HH) flows have been carried out during the past 10 years. These flows are more difficult to compute than extragalactic jets because of the importance of the radiative cooling for the dynamics of HH jets. The cooling distances are usually short, which makes them difficult to resolve in numerical simulations using standard methods. It is even more difficult to predict the observational characteristics of the computed flows, since the line emission depends on the detailed density, temperature and non-equilibrium ionization structure of the post-shock gas.

The axisymmetric and 3D simulations found in the literature are based on different approximations of the ionization state and cooling rate of the flow:

(i) Raga & Böhm (1987), Raga et al. (1988) and Raga (1988) assumed that the ionization state of the gas is given by the coronal ionization equilibrium condition (which is clearly incorrect for the post-shock cooling regions), and used a cooling rate consistent with this assumption.

(ii) Blondin, Königl, & Fryxell (1989) and Blondin, Fryxell, & Königl (1990) used a "non-equilibrium" cooling function, which was computed by Kafatos (1973) for a parcel cooling at constant density from a high temperature. While this cooling rate might mimic some of the non-equilibrium ionization effects found in a recombination region of a shock wave, it is unclear to what extent it departs from a more consistently computed cooling function. Also, these authors quite surprisingly assumed that the gas consists of fully ionized hydrogen (regardless of position), not including the effect of partial ionization on the gas pressure. This assumption leads to a very high cooling rate at low temperatures. To avoid this Blondin et al. introduced an artificial cutoff temperature of $\sim 10^4$ K below which the cooling function was set to zero. An apparently almost identical approach was taken by Gouveia dal Pino & Benz (1993, 1994) and Chernin et al. (1994).

(iii) Stone & Norman (1993ab, 1994ab) explicitly computed the non-equilibrium ionization state of hydrogen (integrating a single ionization rate equation), and used this to obtain the electron density and the densities of the "ionized" and "neutral" components of the gas. These densities were then used to compute an approximate cooling rate. It appears that Stone & Norman neglected cooling due to collisional ionization of hydrogen, leading to an unrealistically high state of ionization behind shocks with velocities ≤ 100 km s^{-1}(moving into mostly neutral gas). An equivalent approach was taken by Raga (1994), Falle & Raga (1995), Biro, Raga, & Cantó (1995), though these authors included cooling due to collisional ionization of hydrogen, and in some cases (Raga et al. 1995) also cooling due to the presence of H_2 molecules.

The axisymmetric, nonadiabatic simulations made previously by Ròżyczka & Tenorio-Tagle (1985) apparently used an approach similar to the ones described in (i) or (ii) However, they do not give an extensive description of their treatment of the cooling.

While these three approaches result in a more or less correct description of the dynamical characteristics of the flow, their approximate treatment of the ionization and cooling is likely to lead to unrealistic predictions of the emitted spectrum. Also, the numerical resolution of the post-shock flow in these calculations is too coarse to obtain reliable predictions of the emitted spectrum. The lack of resolution can to some extent be solved by computing only a limited region of an HH flow (as in the bow shock models of Raga & Böhm 1987) and/or using an adaptive computational grid as done by Falle & Raga (1993, 1995) and Raga (1994).

Because of these limitations, most of the detailed comparisons between model predictions and observations of HH objects have been based on applications of "quasi-1D" bow shock models (e.g., Hartmann & Raymond 1984; Choe, Böhm, & Solf 1985; Raga & Böhm 1985, 1986; Hartigan, Raymond, & Hartmann 1987; Hartigan, Raymond, & Meaburn 1990). In these models, a surface that approximately reproduces the shape of the bow shock is considered, and the emission from the post-shock region is computed by assuming that the surface locally has an emission identical to the one from a plane, steady shock of the corresponding shock velocity. These plane shocks allow a detailed treatment of ionization, cooling and radiative transfer effects (see, e.g., Raymond 1979; Hartigan et al. 1987). It is thought (though not proven) that this approximate approach is valid for flow parameters that produce cooling distances which are much shorter than the radius of the bow shock. As it is unclear to what extent these quasi-1D models are realistic approximations of a bow shock, it is of obvious interest to calculate an axisymmetric, physically more realistic simulation of the flow. This is now computationally possible.

An example of this is the method for including non-equilibrium cooling in a gas dynamics code described by Frank & Mellema (1994a). This code was used to study the formation and evolution of (largely) photo-ionized nebulae, such as Planetary Nebulae

(Frank & Mellema 1994b, Mellema & Frank 1995, Mellema 1995). The success of this approach was one of the motivations for the current work. An important difference between their and our method (apart from the photo-ionization) is that they used analytical fits to the different cooling rates and atomic rates (see Balick, Mellema, & Frank 1993), whereas we use look-up tables which include more processes.

Another modern development helpful in studying the gas dynamics of problems with short cooling distances is the adaptive grid approach. An adaptive grid provides a huge improvement in both memory and computing time requirements, and makes it possible to carry out numerical simulations which include an extensive set of microphysical processes (e.g., rate equations describing ionization and/or chemical processes for a number of species). Clearly, such an approach results in a much more realistic description of both the flow and its observational characteristics.

We have selected a set of 18 ionization rate equations for the species necessary to obtain realistic cooling rates for shock velocities up to ~ 200 km s^{-1}. This paper presents a detailed description of our ionization and cooling rate calculations, as well as a quantitative evaluation of the resulting cooling function (§2). In §3 we then present results for a high-resolution, adaptive grid simulation of a bow shock formed around a rigid sphere, in which we have used our description of the ionization and cooling. The results from this simulation are used to illustrate the detailed characteristics of a radiative bow shock flow, and to compare with the results from a "quasi-1D" model. Finally, in Appendix A we present details of the ionization, recombination and cooling rates which we have used, including tables for the cooling rates. This should facilitate implementations of this network into other gas dynamic codes.

2. A simplified ionization and cooling rate network

We consider a reduced set of rate equations describing the time-evolution of the non-equilibrium ionization fractions of H II, C III-IV, N II-V, O II-V, S III-V and Ne II-V. We assume that C and S are always at least singly ionized, and complete this set of rate equations with the conservation condition for all of the ions of each element. The processes we include are collisional ionization, radiative and dielectronic recombination, and charge exchange processes of different ions with H and H^+. A more detailed description of this is given in Appendix A.

The rate equations for the ions can be integrated in step with the appropriate dynamical equations. The resulting ion and electron densities can then be used to calculate the cooling rate L (energy per unit volume and time). In our prescription of L, we include hydrogen collisional excitation of Lyman-α, as well as radiative recombination and free-free emission. For the other ions we include collisional excitation of optical and ultraviolet lines. A complete tabulation of the cooling rate $L_{iz}/(n_e n_{iz})$ for each ion of species i and charge z is given in Tables 1-11 (see Appendix A).

To test the accuracy of our reduced set of ions and the resulting cooling function, we computed the evolution of a parcel that cools at constant density from a high initial temperature. We have considered a parcel with a number density (atoms plus ions) $n = 1$ cm^{-3}, cooling from an initial temperature $T_1 = 10^6$ K, and recombining from coronal ionization equilibrium evaluated at this temperature. The same problem was studied by Innes (1985), who, however, considered a much larger set of ions and lines.

Figure 1 shows a comparison between the time-dependent cooling function using our reduced set of ionization rate equations, and the more complete calculation of Innes (1985). At temperatures above 2×10^5 K our cooling function is lower than the one of Innes (1985) by a factor of ~ 2. This is because our set of equations extends only to ions of ionization stage V. One more ionization stage is necessary to compute a model that starts at $T_1 = 10^6$ K. However, below 2×10^5 K, our simplified prescription results in a cooling function that deviates by less than 20 % from Innes (1985).

Another interesting check of our reduced set of equations is to compute models of steady, planar shocks. We included the cooling function in the differential equation for the evolution of the enthalpy, which is integrated simultaneously with the ionization rate equations (see, e.g., Raymond 1979). We have computed a set of models with a pre-shock density $n_0 = 100$ cm^{-3}, and shock velocities $v_s = 40$, 60, 80, 100, 120, 140, 160 and 180 km s^{-1}. We have computed this set of models twice, one time for the case of a neutral pre-shock gas (except for C and S, which are always at least singly ionized, see above), and another for singly ionized H and O.

To compare with previous, more detailed shock wave models, we computed the distances at which the post-shock gas has cooled to 10^4 K and 10^3 K, d_4 and d_3 respectively. We plot these cooling distances as a function of shock velocity v_s in Figure 2.

In this figure, we have also plotted d_4 and d_3 for the shock models of Hartigan et al. (1987). These authors considered a very extensive number of processes, and included a detailed treatment of the radiative transfer of ionizing radiation. Figure 2 includes the values of d_4 and d_3 for the two sets of shock models tabulated by Hartigan et al. (1987). One of these corresponds to "self-consistent preionization" calculations in which the ionization state of the pre-shock gas is set in a self-consistent way by the ionizing radiation from the post-shock gas. In the second set ("fully preionized" models), it is assumed that the pre-shock gas has fully ionized hydrogen.

From Figure 2, we see that the d_4 cooling distance calculated from our "fully preionized" models agrees very well for all shock velocities with the values obtained from the corresponding models of Hartigan et al. (1987). A reasonably good agreement is also obtained for the d_3 cooling distance, except for $v_s = 40$ km s^{-1}. For this velocity there is a discrepancy of a factor ~ 3.

We find (see Fig. 2) that our "neutral pre-shock gas" models predict values of d_4 that are in reasonably good agreement with the values obtained from the "self-consistent pre-ionization" models of Hartigan et al. (1987) for shock velocities $v_s \geq 80$ km s^{-1}. Deviations by a factor of ~ 4 are found for the two models with lower velocity. A reasonably good agreement is also found between the values of d_3 predicted from the shock models with $v_s \geq 100$ km s^{-1}, though discrepancies of a factor of ~ 10 are found for lower velocities.

From this it is clear that our reduced set of ionization rate equations produces shock models that are quite similar to the much more detailed calculations of Hartigan et al. (1987). The main deviations occur in the low temperature tail of the recombination region. Comparing the d_4 cooling distance with other codes (which all have more detailed treatments of ionization and cooling than ours), we find that our models appear to fall well within the quite broad range of predictions produced by these codes, as is clear from a comparison with the tabulations of Péquignot (1986) and Ferland et al. (1995). As these tabulations of shock models do not include the d_3 cooling distance, it is not clear whether the discrepancies in d_3 between our code and the one of Hartigan et al. (1987) are particularly extreme (see above).

The main drawback of our approach is that we do not consider the radiative transfer of ionizing radiation. This limits us to treat pre-ionization as a free parameter, which is a shortcoming especially at shock velocities around $v_s \approx$ 80-100 km s^{-1}(see, e.g., Shull and McKee 1979). However, it is at the present stage premature to include radiative transfer of the diffuse ionizing radiation field in axisymmetric or 3D numerical simulations. This should be the objective for future simulations. Here we mainly test our reduced set of equations, which is a first step towards calculations which include proper radiative transfer.

3. A simulation of a radiative, blunt-body flow

We have implemented our ionization and cooling rate prescription in the axisymmetric, adaptive grid code Coral. Coral has been used quite extensively for computing HH flows, albeit with a more simplified treatment of the microphysical processes (see, e.g., Raga et al. 1995).

In the present configuration, a set of 23 equations is integrated: the 4 gasdynamic equations, 18 equations for the atomic and ionic species, and 1 equation for an inert dye (which is used to trace material surfaces). This represents an increase by a factor of $\sim$ 3-5 in number of equations with respect to all previous numerical simulations of HH flows in the literature (see §1). With our formalism, we can calculate more realistic models of HH flows, especially in terms of the relevant atomic processes (see §2). As an illustration of this capability, we have chosen to compute a relatively simple, blunt-body flow, such as the one computed in the past by Raga & Böhm (1987).

The supersonic, blunt-body flow problem is not a very realistic description of the flow expected in the ISM, but it has the clear advantage that a single, main shock (i.e., the bow shock) is produced. This simplicity allows a more detailed comparison with the results from planar shock and quasi-1D bow shock models. In future papers, we will present simulations of more complex flows (e.g., the working surface of a jet).

We have considered a rigid, spherical obstacle of radius $R_c = 10^{16}$ cm interacting with a plane-parallel incident stream of gas of velocity $v_0 = 80$ km s^{-1} and temperature $T_0 = 1000$ K. This value for the velocity was chosen to be well under the limit of 100-120 km s^{-1} above which the post-shock region would become thermally unstable (see, e.g., Falle 1981; Raga & Böhm 1987). The incident stream is assumed to have a hydrogen ionization fraction of 10^{-3}, and a number density of $n_0 = 2.63$ cm^{-3}. For a steady, plane shock model with these parameters, one obtains a cooling distance $d_4 = 10^{15}$ cm$= R_c/10$.

The calculation is started with the plane flow in contact with the surface of the obstacle. The system of equations is first integrated up to a time $t_1 = 65$ yrs in a domain of extent of 1.5×10^{16} cm (in both the axial and radial directions) with a 5-level, binary adaptive (cylindrical) grid (see Raga et al. 1995) of minimum grid spacing $\Delta = 5.86 \times 10^{13}$ cm (in both axial and radial directions, which would correspond to a uniform grid of 256×256 points for the chosen grid size). Then, the maximum resolution of the grid is doubled, so that $\Delta = 2.93 \times 10^{13}$ cm, and the integration is continued until $t_2 = 85$ yrs. Finally, the resolution is doubled again, resulting in a minimum grid spacing $\Delta = 1.46 \times 10^{13}$ cm, and the numerical integration is continued until $t_3 = 105$ yrs. The final flow (which we discuss in detail below) is therefore computed in a grid that corresponds to a uniform grid of 1024×1024 points. The adaptive grid at the end of the integration, however, has a filling factor of only 12 % (with respect to a uniform grid).

The temperature, density and pressure distributions of this numerical integration are shown in Figure 3, along with a representation of the adaptive grid. One of the most striking features is that the flow is non-steady (this is apparent from Fig. 3, even though this figure only shows a single snapshot). This result may at first seem surprising, since the flow parameters were chosen so as to produce a thermally stable bow shock (see above). However, a more thorough check shows that the non-steady features of the flow appear to be associated with a cool (1.0-1.5$\times 10^4$ K), dense layer that is formed around the head of the obstacle. The material in this dense layer flows outwards along the surface of the obstacle, and detaches from the obstacle when the cylindrical radius is $r_d \approx$ 0.8-0.9 R_c. The region between the detached layer and the obstacle is filled with low density, cool material. We speculate that the time-dependent features of the bow shock might be associated with "thin shell instabilities" developing in this dense, cool layer (Dgani, Van Buren, & Noriega-Crespo 1996).

Another result that may seem surprising is that the standoff distance of the stagnation region is only $\approx 4.7 \times 10^{14}$ cm, which is roughly equal to 1/2 of the cooling distance $d_4 = 10^{15}$ cm for a steady, plane shock of the same pre-shock parameters. This goes against the standard expectation that the standoff distance should be approximately equal to d_4.

However, a close look at the structure of the recombination region behind an 80 km s^{-1}, plane shock (as computed, e.g., by Raga 1989) shows that the d_4 cooling distance does not correspond to a point where a drastic compression occurs in the post-shock flow (as it does for shock velocities $\geq$ 120 km s^{-1}). Actually, the largest compression occurs in the region where hydrogen is collisionally ionized right after the shock. As d_4 therefore does not have any clear dynamical significance, it is not surprising that the standoff distance does not have the same value as the cooling distance.

This has quite interesting implications for the application of "quasi-1D" bow shock models (in which the post-bow shock emission is approximated with locally one-dimensional recombination regions, see §1). From the above discussion we would conclude that it is not possible to model bow shocks of velocities $\leq$ 100 kms with quasi-1D models, even when the cooling distance is much smaller than the bow shock radius. This is because the standoff distance is considerably smaller than the cooling distance. A substantial part of the emission is produced in regions where the streamlines are heavily curved, producing both dynamical and thermal structures which are different from the ones in a 1D shock model.

This can be quantified to some extent by analysing cuts across the bow shock structure obtained from our numerical simulation. As shown in Figure 4, we have chosen three cuts (a, b and c) across the flow, taken perpendicular to the bow shock at different distances from the symmetry axis.

The flow along the on-axis cut (a, see Fig. 4) is shown in Figures 5 and 6. Figure 5 shows the temperature, number density and pressure, plotted as a function of a coordinate l, which is measured from the bow shock along the direction of the cut. The ordinate of the plot extends up to the position of the rigid body. Figure 6 shows the ionization fractions of H II, O II and O III along the same cut. Also shown in Figures 5 and 6 are the corresponding variables predicted from a steady, plane shock of the same pre-shock parameters.

If we compare the structure of the plane shock with the one measured along cut a (Figs. 4, 5 and 6), it is evident that the differences are not very large. The small observed differences could at least partially be due to the lower resolution of the axisymmetric simulation, resulting in inaccuracies in the computed structure of the cooling region. From this, we would conclude that the on-axis structure of the bow shock approximately corresponds to a plane shock model which is "truncated" at $l \sim d_4/2$.

The flow and ionization structure across cut b (see Fig. 4) are shown in Figures 7 and 8. These also include the corresponding variables as predicted from a plane shock of velocity $v_s = 66.4$ km s^{-1}(which is the velocity that corresponds to the projection of the preshock velocity normal to the local bow shock surface). The other preshock parameters are identical to the ones of the bow shock model. Differences between the axisymmetric simulation and the plane shock model are now much more obvious than for cut a. At $l \approx 10^{14}$ cm, the post-bow shock divergence of the streamlines results in densities that are substantially lower than the ones of a plane shock model (see Fig. 7). At $l \approx 10^{15}$ cm, we start to see more highly ionized material (see Fig. 8). This is gas which has gone through the stronger shocks found closer to the symmetry axis and has then moved away towards the bow shock wings.

Finally, the flow and ionization structure across cut c (see Fig. 4) are shown in Figures 9 and 10. Here we also show the structure of a plane shock of velocity $v_s = 40.2$ km s^{-1}(which corresponds to the projection of the preshock velocity normal to the local bow shock surface). We now find an almost complete lack of correspondence between the structures predicted from the numerical simulation and from the bow shock models, except immediately behind the shock. The bow shock model has a dramatically higher ionization than the plane shock at distances $l \sim 1.0\text{-}1.7 \times 10^{15}$ cm (Fig. 10). This partially ionized region has temperatures ranging between 1000-12000 K (Fig. 9), and corresponds to gas that has gone through stronger shocks closer to the symmetry axis. This gas has a "frozen in" ionization state as a result of the adiabatic expansion that it has undergone in going around the rigid obstacle.

An interesting feature seen in cut b, and even more strongly in cut c, is the presence of a clear pressure gradient in the post-bow shock region (see Figs. 7 and 9), which is absent in the structures found from all plane shock models. This pressure gradient is due to the so-called "centrifugal effect", and is necessary for forcing the postshock material to follow a curved trajectory, along the surface of the obstacle.

It should be pointed out again that our simulation has the important limitation of corresponding to a bow shock formed around a rigid body (which is of course not very realistic for the case of a flow in the ISM). However, this simulation would be directly applicable for describing the early stages of the interaction of a high velocity, low density wind with a dense, spherical cloud. The evolution of this interaction, however, will lead to a clear deformation of the cloud (and to complex effects involving mixing between the wind and cloud material). All of these effects will clearly lead to more major departures (than the ones described above) from the simple picture invoked in a quasi-1D bow shock model.

4. Discussion

In this paper, we have presented a description of a reduced set of ionization rate equations, which has been devised for incorporating into 2D or 3D gasdynamic simulations of HH flows, but parts of which might be applied to other astrophysical flows as well (PNe, SN, etc.). Through a comparison with the time-dependent cooling function of Innes (1985), we find that the cooling function computed using only the contributions from our reduced set of ions is acceptably accurate in the $10^4 - 10^6$ K temperature range.

We then compute steady, plane shock models with this ionization rate equation set, and compare the cooling distances found for shocks of velocities $v_s = 40$ to 180 km s^{-1} with the corresponding predictions from the much more detailed models of Hartigan et al. (1987). We again find a good agreement. From this comparison, we also find that the main limitation of our approach is that we do not include radiative transfer of the ionizing radiation. Unfortunately, this is crucial for determining the amount of preionization of the gas that enters the shock wave. At present we are forced to treat the preionization as a free parameter. As it is quite complex to incorporate radiative transfer in 2D or 3D gasdynamic simulations, we have not yet attempted to carry out this important step. This is left for a future study.

Finally, we present an axisymmetric simulation of a bow shock formed around a rigid obstacle. This problem was chosen because of the relative simplicity of the resulting shock structure, and also because of its relevance for HH flows. Even though the computed model has a relatively short cooling distance of 1/10 of the radius of the obstacle, we find that the recombination region behind the bow shock deviates quite radically from what is predicted from "quasi-1D" models, based on a superposition of oblique, 1D shock models.

Although this result cannot be directly applied to HH objects (which are not rigid obstacles), it does show that quasi-1D bow shock models are not really appropriate for describing flows of this type. For example, we find shorter standoff distances and higher ionization conditions in the wings than in these types of models. This would suggest that the results of the analysis of HH spectra using quasi-1D bow shock models should be used with some caution.

In order to carry out comparisons of our models with real HH objects we need to compute jet models of the type described in §1. With the details from the non-equilibrium ionization calculations, it will be possible to present the ionization stratification distribution, and using the velocity information, line profiles. In a second paper we will present the results of such an axisymmetric simulation and a detailed comparison with observations of HH objects.

GM thanks the IAUNAM for a very pleasant stay in Mexico City, during which the bulk of this work was carried out. GM's stay at the IAUNAM as well as part of the work of ACR was supported by the DGAPA (UNAM) grant IN 105295 and the UNAM-Cray grant SC-004596. ACR and GM thank Jorge Cantó, Will Henney, and Jane Arthur for useful discussions. The research of PL is supported by the Swedish Natural Science Research Council.

A. Appendix A

As discussed in §2, we have included the ions H I-II, C II-IV, N I-V, O I-V, Ne I-V and S II-V in the ionization rate equations and the cooling function. These ions constitute the major part of the cooling for temperatures of up to a few $\times 10^5$ K, except for sulphur which was included because of its importance for nebular analysis. The abundances (by number) we have used are $x_H = 0.999$, $x_C = 3.3 \times 10^{-4}$, $x_O = 6.6 \times 10^{-4}$, $x_{Ne} = 8.3 \times 10^{-4}$ and $x_S = 1.6 \times 10^{-5}$. Except for hydrogen, these abundances correspond to average cosmic values. Helium was excluded since it is uninteresting for diagnostic purposes, and does not have a strong effect on the cooling. Obviously, this omittance also speeds up the calculations slightly. In our equation of state, we have assumed that the hydrogen atoms have an increased mass of $1.3 \times m_H$. This is equivalent to including helium in the equation of state assuming an He/H-ratio (by number) of 0.10. However, we do not take into account the fact that helium and hydrogen have different ionization potentials.

In the ionization rate equations we have considered collisional ionization, radiative and dielectronic recombination, as well as charge exchange reactions with hydrogen. Data for these processes, as well as the cooling discussed below, overlap to a large extent with the more complete data set used by Lundqvist & Fransson (1996) and Lundqvist et al. (1996). However, for the sake of completeness we discuss the atomic data here too.

For hydrogen we have used the Case A recombination coefficient of Seaton (1959), and the collisional ionization coefficient from Cox (1970). For some of the ions (C II, N II, O III, S II and S III) we have used the complete recombination rates (radiative + dielectronic) of Nahar (1995). For the other ions we have used a combination of different radiative and dielectronic rates. For recombination to N I, N III, O II, O IV, Ne I-IV and S IV we have included the radiative rates of Landini & Monsignori Fossi (1990), for recombination to C III and N IV those of Arnaud & Rothenflug (1985), and for recombination to O I that of Chung, Lin, & Lee (1991). Low-temperature dielectronic rates for recombination to C III, N I, N IV and O II were taken from Nussbaumer & Storey (1983), to Ne II-IV from Nussbaumer & Storey (1987), whereas for S IV we have used the approximate rate from Lundqvist & Fransson (1991). In addition to this, we have included the high-temperature rates of Landini & Monsignori Fossi (1990) for recombination to C III, N I, N IV, O II and Ne I-IV, the rates coveraging a wider temperature range calculated by Badnell (1987, 1991) for recombination to N III and S II-IV, and by Badnell & Pindzola (1989) for recombination to O I-II and O IV. Collisional ionization of C, N and O was taken from Landini & Monsignori Fossi (1990) with slight adjustment to agree better with the results of Lotz (1967). For Ne and S the detailed fits of Arnaud & Rothenflug (1985) were used. For charge transfer reactions with hydrogen we have considered the same rates as in the comprehensive compilation of Kingdon & Ferland (1996).

Hydrogen cooling was assumed to be due to collisional ionization and collisional excitation of Ly-α, using the collision strength of Aggarwal (1983). Metal cooling was calculated using multi-level models for C II-III, N I-III, O I-IV, Ne III-V and S II-IV. For the other ions we only considered the most important allowed and semi-forbidden transitions. The resulting cooling rate per electron, and per ion of species i and charge z, $\Lambda_{i,z} = L_{i,z}/(n_{i,z} n_e)$, is given in Tables 1-10 for C I-III, O I-IV and Ne I-V for a wide range of temperatures (10^2 – 10^6 K) and electron density (1.0 – 10^6 cm^{-3}). (Note that we have included the C I cooling in these tables, even though it was not incorporated in our hydro simulations). The first column of the tables gives the values of $\log_{10} T_e$ (with T_e in K), and the 13 following columns give the values of $\log_{10} \Lambda_{i,z}$ (with $\Lambda_{i,z}$ in erg cm^{3}s^{-1}) for equidistant values of $\log_{10} n_e$ (with n_e in cm^{-3}), respectively.

The atomic data we have used are to a fair extent from Gaetz & Salpeter (1983), Mendoza (1983), Gallagher & Pradhan (1985), Aggarwal et al. (1986) and Osterbrock (1989). We have added and updated data for C II (Biémont, Delahaye, & Zeippen 1994; Peng & Pradhan 1995), C III (Allard et al. 1990; Keenan, Feibelman, & Berrington 1992; Fleming, Hibbert, & Stafford 1994), N II (Stafford et al. 1994) N III (Stafford, Bell, & Hibbert 1994; Brage, Froese-Fischer, & Judge 1995; Peng & Pradhan 1995), O II (McLaughlin & Bell 1993), O III (Aggarwal 1993) and O IV (Zhang, Graziani, & Pradhan 1994; Peng & Pradhan 1995). Although not included in our tables, the S II model ion included the results of Cai & Pradhan (1993) and Keenan et al. (1993).

As can be seen from Tables 1-10, $\Lambda_{i,z}$ decreases with increasing density. This is due to collisional de-excitation which suppresses forbidden transitions in the range of densities we consider. For some of the ions (H I, C IV and O V), only allowed transitions contribute. These transitions are not affected by collisional de-excitation in our density range (Table 11). We have assumed that this also applies to the recombination emission of H II (cf. Table 11), which is a good approximation.

In calculating the cooling, we have not considered optical depth effects in the lines. The main effect is that resonance lines shortward of the Lyman edge of hydrogen may contribute to the ionization of hydrogen elsewhere in the flow. Considering the fact that we do not include helium in our models, nor ionization due to the diffuse continuum emission, this effect is unimportant. At low temperatures the omission of optical depth effects in low-lying fine structure lines can result in an overestimate of the cooling, but probably not to the level of other uncertainties in our calculations.

Table 1. C I cooling

2.0	-23.663	-23.672	-23.700	-23.774	-23.932	-24.170	-24.448	-24.780	-25.190	-25.654	-26.142	-26.638	-27.137
2.1	-23.560	-23.572	-23.609	-23.705	-23.899	-24.176	-24.473	-24.795	-25.188	-25.643	-26.126	-26.621	-27.119
2.2	-23.458	-23.474	-23.521	-23.641	-23.873	-24.189	-24.512	-24.830	-25.200	-25.639	-26.116	-26.609	-27.106
2.3	-23.358	-23.379	-23.438	-23.583	-23.851	-24.205	-24.561	-24.884	-25.230	-25.646	-26.112	-26.600	-27.097
2.4	-23.261	-23.287	-23.360	-23.532	-23.832	-24.220	-24.611	-24.955	-25.284	-25.668	-26.115	-26.596	-27.090
2.5	-23.167	-23.199	-23.287	-23.486	-23.816	-24.229	-24.655	-25.035	-25.364	-25.713	-26.131	-26.597	-27.086
2.6	-23.076	-23.116	-23.221	-23.445	-23.800	-24.234	-24.687	-25.109	-25.467	-25.794	-26.168	-26.609	-27.087
2.7	-22.990	-23.038	-23.160	-23.411	-23.787	-24.235	-24.706	-25.163	-25.569	-25.909	-26.244	-26.640	-27.095
2.8	-22.909	-22.966	-23.107	-23.381	-23.775	-24.234	-24.715	-25.194	-25.645	-26.037	-26.368	-26.712	-27.123
2.9	-22.834	-22.900	-23.061	-23.357	-23.765	-24.231	-24.718	-25.208	-25.687	-26.132	-26.514	-26.842	-27.193
3.0	-22.765	-22.842	-23.021	-23.337	-23.757	-24.227	-24.712	-25.193	-25.650	-26.071	-26.468	-26.851	-27.215
3.1	-22.157	-22.246	-22.427	-22.722	-23.118	-23.571	-24.034	-24.466	-24.831	-25.149	-25.502	-25.926	-26.396
3.2	-22.032	-22.142	-22.350	-22.667	-23.059	-23.449	-23.758	-23.952	-24.090	-24.273	-24.575	-24.985	-25.451
3.3	-21.904	-22.030	-22.248	-22.541	-22.830	-23.027	-23.128	-23.187	-23.270	-23.443	-23.750	-24.164	-24.632
3.4	-21.749	-21.870	-22.052	-22.244	-22.375	-22.438	-22.469	-22.504	-22.584	-22.766	-23.084	-23.503	-23.965
3.5	-21.532	-21.622	-21.734	-21.825	-21.873	-21.894	-21.911	-21.943	-22.029	-22.222	-22.549	-22.964	-23.402
3.6	-21.259	-21.313	-21.370	-21.409	-21.428	-21.438	-21.451	-21.486	-21.579	-21.783	-22.112	-22.509	-22.887
3.7	-20.968	-20.997	-21.026	-21.043	-21.052	-21.059	-21.073	-21.110	-21.210	-21.422	-21.745	-22.098	-22.387
3.8	-20.691	-20.707	-20.721	-20.730	-20.735	-20.741	-20.755	-20.797	-20.903	-21.118	-21.419	-21.706	-21.904
3.9	-20.438	-20.446	-20.454	-20.459	-20.463	-20.468	-20.484	-20.528	-20.640	-20.851	-21.115	-21.330	-21.458
4.0	-20.208	-20.213	-20.217	-20.221	-20.223	-20.229	-20.246	-20.294	-20.409	-20.609	-20.829	-20.982	-21.066
4.1	-20.000	-20.003	-20.006	-20.008	-20.010	-20.016	-20.035	-20.085	-20.202	-20.387	-20.566	-20.675	-20.733
4.2	-19.812	-19.814	-19.816	-19.817	-19.820	-19.827	-19.846	-19.900	-20.018	-20.187	-20.333	-20.414	-20.456
4.3	-19.645	-19.646	-19.647	-19.649	-19.651	-19.659	-19.680	-19.738	-19.856	-20.013	-20.134	-20.196	-20.230
4.4	-19.497	-19.498	-19.499	-19.500	-19.503	-19.511	-19.535	-19.597	-19.718	-19.863	-19.966	-20.017	-20.045
4.5	-19.369	-19.369	-19.370	-19.371	-19.374	-19.383	-19.410	-19.477	-19.600	-19.737	-19.828	-19.870	-19.895
4.6	-19.257	-19.257	-19.258	-19.259	-19.263	-19.273	-19.302	-19.375	-19.501	-19.632	-19.713	-19.750	-19.773
4.7	-19.159	-19.160	-19.160	-19.162	-19.166	-19.177	-19.211	-19.289	-19.419	-19.545	-19.618	-19.652	-19.673
4.8	-19.074	-19.075	-19.076	-19.077	-19.082	-19.095	-19.132	-19.217	-19.350	-19.472	-19.540	-19.570	-19.591
4.9	-19.000	-19.000	-19.001	-19.003	-19.008	-19.023	-19.064	-19.157	-19.293	-19.411	-19.474	-19.503	-19.523
5.0	-18.934	-18.934	-18.935	-18.937	-18.942	-18.959	-19.005	-19.105	-19.245	-19.360	-19.419	-19.446	-19.466
5.1	-18.874	-18.874	-18.875	-18.878	-18.884	-18.903	-18.954	-19.061	-19.205	-19.316	-19.372	-19.397	-19.417
5.2	-18.820	-18.820	-18.821	-18.824	-18.831	-18.852	-18.909	-19.024	-19.170	-19.278	-19.331	-19.355	-19.375
5.3	-18.769	-18.770	-18.771	-18.774	-18.782	-18.806	-18.869	-18.991	-19.139	-19.245	-19.295	-19.318	-19.339
5.4	-18.722	-18.723	-18.724	-18.727	-18.736	-18.763	-18.832	-18.962	-19.113	-19.215	-19.263	-19.286	-19.307
5.5	-18.677	-18.678	-18.679	-18.683	-18.693	-18.723	-18.799	-18.936	-19.089	-19.188	-19.234	-19.256	-19.279
5.6	-18.634	-18.635	-18.636	-18.640	-18.652	-18.686	-18.769	-18.913	-19.067	-19.164	-19.207	-19.229	-19.253
5.7	-18.593	-18.593	-18.595	-18.599	-18.612	-18.650	-18.740	-18.892	-19.046	-19.140	-19.182	-19.204	-19.229
5.8	-18.552	-18.553	-18.554	-18.559	-18.574	-18.616	-18.714	-18.873	-19.027	-19.118	-19.159	-19.180	-19.207
5.9	-18.512	-18.512	-18.514	-18.520	-18.537	-18.583	-18.689	-18.855	-19.009	-19.097	-19.136	-19.158	-19.186
6.0	-18.472	-18.473	-18.475	-18.481	-18.500	-18.551	-18.666	-18.837	-18.991	-19.076	-19.114	-19.136	-19.167

Table 2. C II cooling

2.0	-20.565	-20.728	-21.027	-21.438	-21.905	-22.394	-22.891	-23.390	-23.890	-24.389	-24.889	-25.389	-25.889
2.1	-20.530	-20.691	-20.987	-21.395	-21.862	-22.351	-22.847	-23.346	-23.846	-24.346	-24.846	-25.345	-25.845
2.2	-20.512	-20.668	-20.959	-21.365	-21.830	-22.319	-22.815	-23.314	-23.814	-24.313	-24.813	-25.313	-25.813
2.3	-20.505	-20.657	-20.942	-21.344	-21.808	-22.295	-22.792	-23.290	-23.790	-24.290	-24.790	-25.290	-25.790
2.4	-20.509	-20.654	-20.932	-21.329	-21.791	-22.278	-22.774	-23.273	-23.772	-24.272	-24.772	-25.272	-25.772
2.5	-20.521	-20.659	-20.928	-21.320	-21.779	-22.265	-22.761	-23.259	-23.759	-24.259	-24.759	-25.259	-25.759
2.6	-20.539	-20.670	-20.930	-21.314	-21.770	-22.255	-22.751	-23.249	-23.749	-24.248	-24.748	-25.248	-25.748
2.7	-20.563	-20.685	-20.935	-21.312	-21.764	-22.248	-22.743	-23.241	-23.741	-24.240	-24.740	-25.240	-25.740
2.8	-20.591	-20.705	-20.943	-21.312	-21.760	-22.243	-22.737	-23.235	-23.735	-24.234	-24.734	-25.234	-25.734
2.9	-20.622	-20.728	-20.955	-21.314	-21.758	-22.239	-22.733	-23.231	-23.730	-24.230	-24.730	-25.230	-25.730
3.0	-20.656	-20.755	-20.969	-21.319	-21.757	-22.236	-22.729	-23.227	-23.726	-24.226	-24.726	-25.226	-25.726
3.1	-20.683	-20.776	-20.981	-21.322	-21.757	-22.234	-22.727	-23.224	-23.723	-24.223	-24.723	-25.223	-25.723
3.2	-20.712	-20.799	-20.995	-21.327	-21.757	-22.233	-22.725	-23.222	-23.721	-24.221	-24.721	-25.221	-25.721
3.3	-20.743	-20.823	-21.010	-21.334	-21.759	-22.232	-22.723	-23.220	-23.719	-24.219	-24.719	-25.219	-25.719
3.4	-20.774	-20.850	-21.027	-21.341	-21.760	-22.232	-22.722	-23.219	-23.718	-24.218	-24.718	-25.218	-25.718
3.5	-20.807	-20.877	-21.045	-21.349	-21.763	-22.232	-22.721	-23.218	-23.717	-24.215	-24.713	-25.205	-25.680
3.6	-20.840	-20.905	-21.064	-21.358	-21.766	-22.232	-22.719	-23.211	-23.697	-24.159	-24.558	-24.838	-24.985
3.7	-20.874	-20.934	-21.084	-21.367	-21.765	-22.219	-22.680	-23.101	-23.423	-23.608	-23.689	-23.718	-23.728
3.8	-20.902	-20.957	-21.095	-21.358	-21.722	-22.100	-22.396	-22.565	-22.637	-22.662	-22.671	-22.674	-22.675
3.9	-20.893	-20.939	-21.052	-21.260	-21.508	-21.694	-21.787	-21.823	-21.835	-21.839	-21.841	-21.841	-21.841
4.0	-20.768	-20.797	-20.865	-20.977	-21.083	-21.143	-21.168	-21.176	-21.179	-21.180	-21.180	-21.180	-21.180
4.1	-20.492	-20.505	-20.534	-20.578	-20.616	-20.635	-20.642	-20.644	-20.645	-20.646	-20.646	-20.646	-20.646
4.2	-20.143	-20.148	-20.159	-20.175	-20.189	-20.196	-20.199	-20.200	-20.200	-20.200	-20.200	-20.200	-20.200
4.3	-19.792	-19.794	-19.798	-19.805	-19.810	-19.813	-19.814	-19.814	-19.815	-19.815	-19.815	-19.815	-19.815
4.4	-19.464	-19.465	-19.467	-19.469	-19.472	-19.473	-19.474	-19.474	-19.474	-19.474	-19.474	-19.474	-19.474
4.5	-19.169	-19.169	-19.170	-19.171	-19.173	-19.173	-19.173	-19.173	-19.174	-19.174	-19.174	-19.174	-19.174
4.6	-18.912	-18.912	-18.913	-18.913	-18.914	-18.914	-18.914	-18.914	-18.914	-18.914	-18.914	-18.914	-18.914
4.7	-18.696	-18.696	-18.696	-18.696	-18.697	-18.697	-18.697	-18.697	-18.697	-18.697	-18.697	-18.697	-18.697
4.8	-18.519	-18.519	-18.519	-18.519	-18.519	-18.519	-18.520	-18.520	-18.520	-18.520	-18.520	-18.520	-18.520
4.9	-18.378	-18.378	-18.378	-18.378	-18.378	-18.378	-18.378	-18.378	-18.378	-18.378	-18.378	-18.378	-18.378
5.0	-18.268	-18.268	-18.268	-18.268	-18.268	-18.268	-18.268	-18.268	-18.268	-18.268	-18.268	-18.268	-18.268
5.1	-18.184	-18.184	-18.184	-18.185	-18.185	-18.185	-18.185	-18.185	-18.185	-18.185	-18.185	-18.185	-18.185
5.2	-18.123	-18.123	-18.123	-18.123	-18.123	-18.123	-18.123	-18.123	-18.123	-18.123	-18.123	-18.123	-18.123
5.3	-18.079	-18.079	-18.079	-18.079	-18.080	-18.080	-18.080	-18.080	-18.080	-18.080	-18.080	-18.080	-18.080
5.4	-18.050	-18.050	-18.050	-18.050	-18.050	-18.051	-18.051	-18.051	-18.051	-18.051	-18.051	-18.051	-18.051
5.5	-18.033	-18.033	-18.033	-18.033	-18.033	-18.033	-18.033	-18.033	-18.033	-18.033	-18.033	-18.033	-18.033
5.6	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025
5.7	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025	-18.025
5.8	-18.030	-18.030	-18.030	-18.030	-18.030	-18.030	-18.030	-18.030	-18.030	-18.030	-18.030	-18.030	-18.030
5.9	-18.041	-18.041	-18.041	-18.041	-18.041	-18.041	-18.041	-18.041	-18.041	-18.041	-18.041	-18.041	-18.041
6.0	-18.055	-18.055	-18.055	-18.055	-18.055	-18.055	-18.055	-18.055	-18.055	-18.055	-18.055	-18.055	-18.055

Table 3. C III cooling

3.6	-26.012	-26.012	-26.012	-26.012	-26.013	-26.013	-26.013	-26.015	-26.021	-26.033	-26.050	-26.064	-26.071
3.7	-24.377	-24.377	-24.377	-24.377	-24.377	-24.377	-24.378	-24.379	-24.384	-24.395	-24.411	-24.425	-24.432
3.8	-23.089	-23.089	-23.089	-23.089	-23.089	-23.089	-23.090	-23.091	-23.096	-23.106	-23.121	-23.134	-23.140
3.9	-22.078	-22.078	-22.078	-22.078	-22.078	-22.078	-22.078	-22.080	-22.084	-22.093	-22.107	-22.119	-22.126
4.0	-21.284	-21.284	-21.284	-21.284	-21.284	-21.285	-21.285	-21.286	-21.289	-21.298	-21.310	-21.322	-21.329
4.1	-20.659	-20.659	-20.659	-20.659	-20.659	-20.659	-20.659	-20.660	-20.663	-20.670	-20.682	-20.693	-20.700
4.2	-20.155	-20.155	-20.155	-20.155	-20.155	-20.155	-20.155	-20.156	-20.159	-20.165	-20.176	-20.186	-20.192
4.3	-19.733	-19.733	-19.733	-19.733	-19.733	-19.733	-19.733	-19.734	-19.736	-19.741	-19.751	-19.760	-19.766
4.4	-19.365	-19.365	-19.365	-19.365	-19.365	-19.365	-19.365	-19.366	-19.368	-19.373	-19.382	-19.391	-19.396
4.5	-19.043	-19.043	-19.043	-19.043	-19.043	-19.043	-19.043	-19.044	-19.046	-19.051	-19.060	-19.070	-19.076
4.6	-18.766	-18.766	-18.766	-18.766	-18.766	-18.766	-18.767	-18.768	-18.770	-18.776	-18.787	-18.798	-18.805
4.7	-18.538	-18.538	-18.538	-18.538	-18.538	-18.538	-18.538	-18.539	-18.542	-18.549	-18.562	-18.576	-18.584
4.8	-18.354	-18.354	-18.354	-18.354	-18.354	-18.354	-18.355	-18.356	-18.359	-18.367	-18.383	-18.399	-18.408
4.9	-18.212	-18.212	-18.212	-18.212	-18.212	-18.212	-18.212	-18.213	-18.217	-18.226	-18.243	-18.262	-18.273
5.0	-18.104	-18.104	-18.104	-18.104	-18.104	-18.104	-18.104	-18.106	-18.110	-18.119	-18.138	-18.158	-18.171
5.1	-18.025	-18.025	-18.025	-18.025	-18.026	-18.026	-18.026	-18.027	-18.031	-18.041	-18.061	-18.083	-18.097
5.2	-17.971	-17.971	-17.971	-17.971	-17.971	-17.971	-17.972	-17.973	-17.977	-17.987	-18.007	-18.030	-18.045
5.3	-17.937	-17.937	-17.937	-17.937	-17.937	-17.937	-17.937	-17.938	-17.942	-17.952	-17.972	-17.995	-18.011
5.4	-17.918	-17.918	-17.918	-17.918	-17.918	-17.918	-17.918	-17.920	-17.923	-17.933	-17.952	-17.976	-17.992
5.5	-17.912	-17.912	-17.912	-17.912	-17.912	-17.912	-17.912	-17.913	-17.917	-17.926	-17.945	-17.969	-17.985
5.6	-17.916	-17.916	-17.916	-17.916	-17.916	-17.916	-17.917	-17.918	-17.921	-17.929	-17.947	-17.971	-17.988
5.7	-17.929	-17.929	-17.929	-17.929	-17.929	-17.929	-17.929	-17.930	-17.933	-17.941	-17.958	-17.981	-17.998
5.8	-17.948	-17.948	-17.948	-17.948	-17.948	-17.948	-17.948	-17.949	-17.952	-17.959	-17.975	-17.997	-18.014
5.9	-17.972	-17.972	-17.972	-17.972	-17.972	-17.972	-17.972	-17.973	-17.976	-17.982	-17.997	-18.019	-18.036
6.0	-18.000	-18.000	-18.000	-18.000	-18.000	-18.001	-18.001	-18.001	-18.004	-18.010	-18.024	-18.044	-18.061

Table 4. O I cooling

2.0	-23.932	-23.932	-23.933	-23.933	-23.933	-23.935	-23.939	-23.952	-23.986	-24.062	-24.210	-24.474	-24.857
2.1	-23.683	-23.683	-23.683	-23.683	-23.684	-23.685	-23.691	-23.706	-23.745	-23.831	-23.993	-24.271	-24.663
2.2	-23.478	-23.478	-23.478	-23.478	-23.479	-23.481	-23.487	-23.504	-23.550	-23.646	-23.821	-24.113	-24.515
2.3	-23.309	-23.309	-23.309	-23.309	-23.310	-23.312	-23.319	-23.339	-23.390	-23.496	-23.686	-23.992	-24.402
2.4	-23.169	-23.169	-23.169	-23.169	-23.170	-23.172	-23.180	-23.203	-23.260	-23.376	-23.580	-23.899	-24.317
2.5	-23.052	-23.052	-23.052	-23.053	-23.053	-23.056	-23.065	-23.090	-23.153	-23.280	-23.496	-23.827	-24.253
2.6	-22.954	-22.954	-22.955	-22.955	-22.956	-22.959	-22.969	-22.997	-23.065	-23.201	-23.429	-23.772	-24.204
2.7	-22.872	-22.872	-22.872	-22.872	-22.873	-22.877	-22.887	-22.918	-22.992	-23.136	-23.376	-23.729	-24.166
2.8	-22.801	-22.801	-22.801	-22.802	-22.803	-22.807	-22.818	-22.851	-22.931	-23.083	-23.333	-23.695	-24.137
2.9	-22.740	-22.740	-22.740	-22.741	-22.742	-22.746	-22.759	-22.794	-22.878	-23.038	-23.297	-23.668	-24.115
3.0	-22.687	-22.687	-22.687	-22.687	-22.689	-22.693	-22.707	-22.744	-22.833	-23.000	-23.268	-23.646	-24.097
3.1	-22.614	-22.614	-22.615	-22.615	-22.617	-22.622	-22.637	-22.678	-22.775	-22.952	-23.235	-23.625	-24.082
3.2	-22.547	-22.547	-22.547	-22.548	-22.550	-22.555	-22.572	-22.618	-22.721	-22.910	-23.207	-23.607	-24.069
3.3	-22.483	-22.483	-22.483	-22.484	-22.486	-22.492	-22.511	-22.561	-22.672	-22.870	-23.180	-23.589	-24.048
3.4	-22.419	-22.419	-22.419	-22.420	-22.422	-22.429	-22.450	-22.504	-22.620	-22.827	-23.141	-23.532	-23.932
3.5	-22.340	-22.340	-22.341	-22.341	-22.344	-22.351	-22.372	-22.428	-22.543	-22.740	-23.013	-23.294	-23.524
3.6	-22.206	-22.206	-22.206	-22.207	-22.209	-22.216	-22.235	-22.283	-22.378	-22.524	-22.689	-22.822	-22.941
3.7	-21.973	-21.973	-21.973	-21.974	-21.975	-21.980	-21.994	-22.026	-22.085	-22.164	-22.240	-22.305	-22.399
3.8	-21.664	-21.664	-21.664	-21.664	-21.665	-21.668	-21.676	-21.694	-21.725	-21.764	-21.802	-21.848	-21.944
3.9	-21.339	-21.339	-21.339	-21.339	-21.340	-21.342	-21.346	-21.356	-21.373	-21.394	-21.419	-21.463	-21.569
4.0	-21.037	-21.037	-21.037	-21.037	-21.037	-21.039	-21.041	-21.047	-21.057	-21.071	-21.092	-21.141	-21.259
4.1	-20.768	-20.768	-20.768	-20.768	-20.768	-20.769	-20.771	-20.775	-20.782	-20.793	-20.815	-20.870	-21.002
4.2	-20.532	-20.532	-20.532	-20.532	-20.532	-20.533	-20.534	-20.537	-20.543	-20.553	-20.577	-20.641	-20.788
4.3	-20.324	-20.324	-20.324	-20.324	-20.324	-20.325	-20.326	-20.329	-20.334	-20.345	-20.373	-20.447	-20.608
4.4	-20.140	-20.140	-20.140	-20.140	-20.140	-20.141	-20.142	-20.145	-20.150	-20.162	-20.195	-20.281	-20.458
4.5	-19.977	-19.977	-19.977	-19.977	-19.977	-19.977	-19.979	-19.981	-19.987	-20.001	-20.040	-20.140	-20.332
4.6	-19.830	-19.830	-19.830	-19.830	-19.830	-19.831	-19.832	-19.834	-19.841	-19.858	-19.905	-20.019	-20.226
4.7	-19.697	-19.697	-19.697	-19.697	-19.697	-19.698	-19.699	-19.702	-19.709	-19.730	-19.785	-19.916	-20.135
4.8	-19.575	-19.575	-19.575	-19.575	-19.575	-19.576	-19.577	-19.581	-19.589	-19.614	-19.679	-19.827	-20.058
4.9	-19.462	-19.462	-19.462	-19.462	-19.463	-19.463	-19.465	-19.469	-19.479	-19.508	-19.585	-19.750	-19.990
5.0	-19.357	-19.357	-19.357	-19.357	-19.358	-19.358	-19.360	-19.365	-19.377	-19.411	-19.501	-19.683	-19.931
5.1	-19.258	-19.258	-19.258	-19.258	-19.259	-19.259	-19.261	-19.267	-19.281	-19.322	-19.426	-19.624	-19.877
5.2	-19.164	-19.164	-19.164	-19.164	-19.165	-19.165	-19.168	-19.174	-19.191	-19.239	-19.358	-19.572	-19.827
5.3	-19.074	-19.074	-19.074	-19.074	-19.074	-19.075	-19.078	-19.085	-19.106	-19.162	-19.296	-19.524	-19.780
5.4	-18.987	-18.987	-18.987	-18.987	-18.987	-18.989	-18.992	-19.000	-19.024	-19.090	-19.240	-19.481	-19.734
5.5	-18.902	-18.902	-18.902	-18.903	-18.903	-18.904	-18.908	-18.918	-18.946	-19.023	-19.189	-19.441	-19.690
5.6	-18.820	-18.820	-18.820	-18.820	-18.821	-18.822	-18.826	-18.838	-18.872	-18.960	-19.143	-19.402	-19.645
5.7	-18.739	-18.739	-18.739	-18.739	-18.740	-18.742	-18.747	-18.760	-18.800	-18.901	-19.100	-19.365	-19.600
5.8	-18.659	-18.659	-18.660	-18.660	-18.660	-18.663	-18.668	-18.685	-18.730	-18.845	-19.060	-19.329	-19.555
5.9	-18.581	-18.581	-18.581	-18.581	-18.582	-18.584	-18.591	-18.610	-18.664	-18.793	-19.022	-19.292	-19.508
6.0	-18.503	-18.503	-18.503	-18.504	-18.505	-18.507	-18.515	-18.538	-18.600	-18.744	-18.986	-19.255	-19.461

Table 5. O II cooling

3.3	-26.875	-26.875	-26.876	-26.881	-26.893	-26.927	-27.004	-27.165	-27.455	-27.858	-28.322	-28.808	-29.301
3.4	-25.194	-25.194	-25.195	-25.199	-25.211	-25.242	-25.313	-25.465	-25.741	-26.135	-26.592	-27.070	-27.543
3.5	-23.868	-23.868	-23.869	-23.873	-23.883	-23.912	-23.978	-24.119	-24.383	-24.764	-25.205	-25.651	-26.058
3.6	-22.824	-22.824	-22.825	-22.828	-22.838	-22.863	-22.924	-23.056	-23.303	-23.664	-24.072	-24.447	-24.743
3.7	-22.002	-22.002	-22.003	-22.006	-22.014	-22.038	-22.093	-22.214	-22.442	-22.772	-23.123	-23.402	-23.598
3.8	-21.356	-21.356	-21.357	-21.359	-21.367	-21.388	-21.438	-21.547	-21.752	-22.040	-22.321	-22.514	-22.647
3.9	-20.848	-20.848	-20.849	-20.851	-20.858	-20.876	-20.921	-21.018	-21.197	-21.440	-21.654	-21.788	-21.885
4.0	-20.450	-20.450	-20.451	-20.453	-20.459	-20.475	-20.515	-20.601	-20.755	-20.955	-21.117	-21.212	-21.289
4.1	-20.139	-20.139	-20.139	-20.141	-20.146	-20.161	-20.198	-20.274	-20.408	-20.573	-20.698	-20.771	-20.835
4.2	-19.896	-19.896	-19.897	-19.898	-19.903	-19.917	-19.951	-20.022	-20.141	-20.281	-20.382	-20.441	-20.497
4.3	-19.707	-19.707	-19.708	-19.709	-19.714	-19.728	-19.761	-19.828	-19.937	-20.060	-20.146	-20.195	-20.245
4.4	-19.557	-19.557	-19.557	-19.559	-19.563	-19.577	-19.609	-19.674	-19.776	-19.886	-19.960	-20.002	-20.046
4.5	-19.427	-19.427	-19.428	-19.429	-19.434	-19.447	-19.478	-19.539	-19.632	-19.728	-19.789	-19.824	-19.859
4.6	-19.304	-19.304	-19.304	-19.305	-19.310	-19.321	-19.350	-19.405	-19.484	-19.561	-19.609	-19.635	-19.661
4.7	-19.177	-19.177	-19.177	-19.178	-19.182	-19.192	-19.216	-19.262	-19.325	-19.383	-19.418	-19.436	-19.454
4.8	-19.049	-19.049	-19.050	-19.050	-19.053	-19.061	-19.081	-19.117	-19.164	-19.207	-19.232	-19.245	-19.257
4.9	-18.928	-18.928	-18.929	-18.929	-18.931	-18.938	-18.953	-18.981	-19.016	-19.048	-19.066	-19.075	-19.083
5.0	-18.821	-18.821	-18.821	-18.822	-18.824	-18.828	-18.840	-18.861	-18.889	-18.912	-18.926	-18.933	-18.938
5.1	-18.731	-18.731	-18.731	-18.732	-18.733	-18.737	-18.746	-18.762	-18.784	-18.802	-18.813	-18.818	-18.822
5.2	-18.658	-18.658	-18.659	-18.659	-18.660	-18.663	-18.670	-18.683	-18.700	-18.715	-18.724	-18.728	-18.732
5.3	-18.602	-18.602	-18.602	-18.603	-18.603	-18.606	-18.612	-18.622	-18.636	-18.649	-18.656	-18.660	-18.663
5.4	-18.560	-18.560	-18.561	-18.561	-18.561	-18.563	-18.568	-18.577	-18.589	-18.600	-18.606	-18.609	-18.611
5.5	-18.531	-18.531	-18.531	-18.531	-18.531	-18.533	-18.537	-18.544	-18.555	-18.564	-18.570	-18.573	-18.575
5.6	-18.511	-18.511	-18.511	-18.511	-18.512	-18.513	-18.516	-18.523	-18.532	-18.540	-18.545	-18.548	-18.550
5.7	-18.500	-18.500	-18.500	-18.500	-18.500	-18.501	-18.504	-18.510	-18.517	-18.525	-18.530	-18.532	-18.534
5.8	-18.495	-18.495	-18.495	-18.495	-18.496	-18.496	-18.499	-18.504	-18.510	-18.517	-18.522	-18.524	-18.526
5.9	-18.496	-18.496	-18.496	-18.496	-18.496	-18.497	-18.499	-18.503	-18.509	-18.516	-18.520	-18.522	-18.524
6.0	-18.501	-18.501	-18.501	-18.501	-18.501	-18.502	-18.504	-18.507	-18.513	-18.519	-18.523	-18.525	-18.526

Table 6. O III cooling

2.0	-20.660	-20.668	-20.691	-20.757	-20.909	-21.178	-21.549	-21.991	-22.469	-22.961	-23.459	-23.958	-24.458
2.1	-20.543	-20.551	-20.573	-20.635	-20.779	-21.031	-21.384	-21.814	-22.288	-22.779	-23.276	-23.775	-24.275
2.2	-20.450	-20.457	-20.479	-20.538	-20.673	-20.910	-21.248	-21.669	-22.139	-22.629	-23.125	-23.624	-24.124
2.3	-20.378	-20.384	-20.405	-20.461	-20.589	-20.814	-21.140	-21.555	-22.022	-22.511	-23.008	-23.506	-24.006
2.4	-20.323	-20.329	-20.349	-20.403	-20.525	-20.740	-21.058	-21.468	-21.934	-22.422	-22.918	-23.417	-23.917
2.5	-20.284	-20.290	-20.309	-20.360	-20.477	-20.685	-20.997	-21.404	-21.868	-22.356	-22.852	-23.350	-23.850
2.6	-20.259	-20.265	-20.283	-20.332	-20.444	-20.646	-20.953	-21.356	-21.819	-22.306	-22.802	-23.301	-23.800
2.7	-20.246	-20.252	-20.269	-20.316	-20.424	-20.621	-20.921	-21.322	-21.783	-22.270	-22.765	-23.264	-23.763
2.8	-20.245	-20.250	-20.266	-20.310	-20.414	-20.605	-20.900	-21.297	-21.756	-22.242	-22.738	-23.236	-23.736
2.9	-20.252	-20.257	-20.272	-20.314	-20.413	-20.598	-20.887	-21.279	-21.736	-22.222	-22.717	-23.215	-23.715
3.0	-20.266	-20.271	-20.285	-20.325	-20.419	-20.598	-20.880	-21.267	-21.722	-22.206	-22.701	-23.199	-23.699
3.1	-20.287	-20.292	-20.305	-20.342	-20.431	-20.603	-20.878	-21.260	-21.711	-22.195	-22.689	-23.187	-23.687
3.2	-20.314	-20.317	-20.329	-20.364	-20.448	-20.613	-20.881	-21.255	-21.704	-22.186	-22.680	-23.178	-23.677
3.3	-20.344	-20.347	-20.358	-20.390	-20.469	-20.627	-20.886	-21.254	-21.698	-22.179	-22.671	-23.167	-23.665
3.4	-20.377	-20.381	-20.391	-20.419	-20.493	-20.643	-20.894	-21.253	-21.692	-22.164	-22.640	-23.108	-23.577
3.5	-20.412	-20.415	-20.424	-20.450	-20.519	-20.660	-20.900	-21.245	-21.661	-22.083	-22.458	-22.791	-23.154
3.6	-20.442	-20.444	-20.452	-20.476	-20.537	-20.667	-20.887	-21.195	-21.533	-21.811	-22.007	-22.203	-22.494
3.7	-20.448	-20.450	-20.457	-20.476	-20.528	-20.637	-20.817	-21.046	-21.252	-21.384	-21.482	-21.628	-21.891
3.8	-20.402	-20.404	-20.409	-20.423	-20.461	-20.540	-20.661	-20.798	-20.901	-20.964	-21.028	-21.153	-21.401
3.9	-20.294	-20.295	-20.298	-20.307	-20.330	-20.379	-20.451	-20.524	-20.576	-20.611	-20.661	-20.776	-21.010
4.0	-20.145	-20.146	-20.148	-20.153	-20.166	-20.194	-20.235	-20.275	-20.304	-20.328	-20.371	-20.477	-20.697
4.1	-19.990	-19.990	-19.991	-19.994	-20.002	-20.018	-20.042	-20.065	-20.084	-20.102	-20.141	-20.238	-20.442
4.2	-19.844	-19.845	-19.845	-19.847	-19.852	-19.861	-19.876	-19.891	-19.904	-19.919	-19.954	-20.042	-20.226
4.3	-19.711	-19.711	-19.712	-19.713	-19.716	-19.722	-19.732	-19.742	-19.751	-19.764	-19.794	-19.872	-20.033
4.4	-19.579	-19.579	-19.579	-19.580	-19.582	-19.586	-19.592	-19.599	-19.606	-19.616	-19.642	-19.707	-19.838
4.5	-19.427	-19.427	-19.427	-19.428	-19.429	-19.432	-19.436	-19.441	-19.445	-19.453	-19.473	-19.522	-19.618
4.6	-19.244	-19.244	-19.244	-19.244	-19.245	-19.247	-19.249	-19.252	-19.255	-19.261	-19.274	-19.307	-19.370
4.7	-19.040	-19.040	-19.040	-19.040	-19.040	-19.041	-19.042	-19.044	-19.046	-19.050	-19.058	-19.079	-19.117
4.8	-18.837	-18.837	-18.837	-18.837	-18.837	-18.838	-18.839	-18.840	-18.841	-18.843	-18.848	-18.861	-18.884
4.9	-18.654	-18.654	-18.654	-18.654	-18.654	-18.654	-18.655	-18.655	-18.656	-18.657	-18.661	-18.669	-18.683
5.0	-18.497	-18.497	-18.497	-18.497	-18.497	-18.498	-18.498	-18.498	-18.499	-18.500	-18.502	-18.507	-18.516
5.1	-18.368	-18.368	-18.368	-18.368	-18.368	-18.368	-18.368	-18.369	-18.369	-18.369	-18.371	-18.374	-18.381
5.2	-18.264	-18.264	-18.264	-18.264	-18.264	-18.264	-18.264	-18.264	-18.264	-18.265	-18.265	-18.268	-18.272
5.3	-18.181	-18.181	-18.181	-18.181	-18.181	-18.182	-18.182	-18.182	-18.182	-18.182	-18.183	-18.184	-18.187
5.4	-18.117	-18.117	-18.117	-18.117	-18.117	-18.117	-18.117	-18.117	-18.117	-18.118	-18.118	-18.119	-18.121
5.5	-18.069	-18.069	-18.069	-18.069	-18.069	-18.069	-18.069	-18.070	-18.070	-18.070	-18.070	-18.071	-18.073
5.6	-18.036	-18.036	-18.036	-18.036	-18.036	-18.036	-18.036	-18.036	-18.036	-18.037	-18.037	-18.037	-18.039
5.7	-18.015	-18.015	-18.015	-18.015	-18.015	-18.015	-18.015	-18.015	-18.015	-18.016	-18.016	-18.016	-18.017
5.8	-18.005	-18.005	-18.005	-18.005	-18.005	-18.005	-18.005	-18.005	-18.005	-18.005	-18.005	-18.005	-18.006
5.9	-18.002	-18.002	-18.002	-18.002	-18.002	-18.002	-18.002	-18.002	-18.003	-18.003	-18.003	-18.003	-18.004
6.0	-18.007	-18.007	-18.007	-18.007	-18.007	-18.007	-18.007	-18.007	-18.007	-18.007	-18.008	-18.008	-18.009

Table 7. O IV cooling

2.0	-20.687	-20.693	-20.712	-20.768	-20.909	-21.182	-21.575	-22.036	-22.522	-23.018	-23.516	-24.016	-24.516
2.1	-20.279	-20.284	-20.301	-20.348	-20.470	-20.720	-21.097	-21.550	-22.034	-22.529	-23.027	-23.527	-24.026
2.2	-19.974	-19.979	-19.992	-20.033	-20.140	-20.369	-20.730	-21.175	-21.656	-22.150	-22.648	-23.147	-23.647
2.3	-19.750	-19.754	-19.766	-19.801	-19.897	-20.108	-20.454	-20.891	-21.369	-21.862	-22.360	-22.859	-23.359
2.4	-19.591	-19.594	-19.605	-19.636	-19.723	-19.919	-20.252	-20.682	-21.157	-21.649	-22.146	-22.645	-23.145
2.5	-19.483	-19.486	-19.495	-19.524	-19.603	-19.787	-20.107	-20.531	-21.003	-21.494	-21.992	-22.491	-22.990
2.6	-19.416	-19.418	-19.427	-19.453	-19.525	-19.698	-20.007	-20.424	-20.894	-21.384	-21.881	-22.380	-22.879
2.7	-19.381	-19.383	-19.391	-19.414	-19.481	-19.642	-19.940	-20.349	-20.816	-21.305	-21.801	-22.300	-22.800
2.8	-19.371	-19.373	-19.380	-19.401	-19.462	-19.612	-19.896	-20.297	-20.761	-21.249	-21.745	-22.243	-22.743
2.9	-19.382	-19.384	-19.390	-19.409	-19.464	-19.602	-19.871	-20.263	-20.722	-21.208	-21.704	-22.202	-22.702
3.0	-19.409	-19.411	-19.416	-19.433	-19.482	-19.607	-19.861	-20.240	-20.694	-21.179	-21.674	-22.172	-22.672
3.1	-19.449	-19.451	-19.456	-19.470	-19.513	-19.625	-19.861	-20.228	-20.675	-21.157	-21.652	-22.150	-22.649
3.2	-19.500	-19.501	-19.505	-19.517	-19.554	-19.654	-19.872	-20.223	-20.663	-21.142	-21.635	-22.133	-22.632
3.3	-19.558	-19.559	-19.562	-19.573	-19.605	-19.693	-19.891	-20.225	-20.655	-21.131	-21.623	-22.121	-22.620
3.4	-19.623	-19.624	-19.627	-19.636	-19.663	-19.739	-19.917	-20.232	-20.652	-21.124	-21.614	-22.111	-22.610
3.5	-19.693	-19.694	-19.696	-19.703	-19.726	-19.792	-19.951	-20.245	-20.653	-21.119	-21.607	-22.104	-22.603
3.6	-19.767	-19.767	-19.769	-19.776	-19.795	-19.851	-19.991	-20.263	-20.656	-21.116	-21.603	-22.098	-22.597
3.7	-19.844	-19.845	-19.846	-19.851	-19.868	-19.915	-20.037	-20.286	-20.663	-21.116	-21.599	-22.094	-22.593
3.8	-19.924	-19.924	-19.926	-19.930	-19.943	-19.983	-20.089	-20.315	-20.673	-21.117	-21.597	-22.091	-22.588
3.9	-20.006	-20.006	-20.007	-20.011	-20.022	-20.055	-20.146	-20.348	-20.687	-21.120	-21.595	-22.084	-22.570
4.0	-20.089	-20.089	-20.090	-20.093	-20.102	-20.129	-20.206	-20.386	-20.702	-21.119	-21.578	-22.030	-22.424
4.1	-20.169	-20.169	-20.170	-20.172	-20.180	-20.202	-20.266	-20.422	-20.707	-21.088	-21.479	-21.791	-21.975
4.2	-20.231	-20.231	-20.232	-20.234	-20.239	-20.257	-20.308	-20.434	-20.668	-20.963	-21.210	-21.349	-21.407
4.3	-20.234	-20.235	-20.235	-20.236	-20.240	-20.252	-20.287	-20.374	-20.531	-20.706	-20.822	-20.874	-20.893
4.4	-20.122	-20.123	-20.123	-20.123	-20.126	-20.132	-20.151	-20.198	-20.280	-20.364	-20.413	-20.434	-20.441
4.5	-19.886	-19.886	-19.886	-19.886	-19.887	-19.890	-19.898	-19.920	-19.957	-19.995	-20.017	-20.026	-20.029
4.6	-19.582	-19.582	-19.582	-19.582	-19.583	-19.584	-19.588	-19.597	-19.615	-19.633	-19.645	-19.649	-19.651
4.7	-19.276	-19.276	-19.276	-19.276	-19.276	-19.277	-19.278	-19.283	-19.292	-19.303	-19.309	-19.312	-19.314
4.8	-19.000	-19.000	-19.000	-19.000	-19.000	-19.001	-19.002	-19.004	-19.009	-19.016	-19.021	-19.023	-19.024
4.9	-18.767	-18.767	-18.767	-18.767	-18.767	-18.767	-18.768	-18.770	-18.773	-18.778	-18.782	-18.783	-18.784
5.0	-18.577	-18.577	-18.577	-18.577	-18.577	-18.577	-18.578	-18.579	-18.581	-18.585	-18.588	-18.589	-18.590
5.1	-18.426	-18.426	-18.426	-18.426	-18.426	-18.426	-18.426	-18.427	-18.429	-18.431	-18.434	-18.435	-18.436
5.2	-18.307	-18.307	-18.307	-18.307	-18.307	-18.307	-18.307	-18.308	-18.309	-18.311	-18.314	-18.315	-18.316
5.3	-18.215	-18.215	-18.215	-18.215	-18.215	-18.216	-18.216	-18.216	-18.217	-18.219	-18.221	-18.222	-18.223
5.4	-18.146	-18.146	-18.146	-18.146	-18.146	-18.146	-18.146	-18.146	-18.147	-18.149	-18.151	-18.152	-18.152
5.5	-18.095	-18.095	-18.095	-18.095	-18.095	-18.095	-18.095	-18.095	-18.096	-18.097	-18.099	-18.100	-18.100
5.6	-18.059	-18.059	-18.059	-18.059	-18.059	-18.059	-18.059	-18.059	-18.059	-18.060	-18.062	-18.063	-18.064
5.7	-18.035	-18.035	-18.035	-18.035	-18.035	-18.035	-18.035	-18.035	-18.036	-18.037	-18.038	-18.039	-18.040
5.8	-18.022	-18.022	-18.022	-18.022	-18.022	-18.022	-18.022	-18.022	-18.023	-18.023	-18.025	-18.026	-18.027
5.9	-18.018	-18.018	-18.018	-18.018	-18.018	-18.018	-18.018	-18.018	-18.018	-18.019	-18.020	-18.021	-18.022
6.0	-18.021	-18.021	-18.021	-18.021	-18.021	-18.021	-18.021	-18.021	-18.021	-18.022	-18.023	-18.024	-18.025

Table 8. Ne III cooling

2.0	-23.949	-23.949	-23.949	-23.949	-23.950	-23.952	-23.960	-23.983	-24.048	-24.206	-24.500	-24.907	-25.373
2.1	-23.169	-23.169	-23.169	-23.169	-23.170	-23.172	-23.179	-23.200	-23.260	-23.407	-23.688	-24.086	-24.548
2.2	-22.557	-22.557	-22.557	-22.557	-22.558	-22.560	-22.567	-22.586	-22.642	-22.779	-23.046	-23.436	-23.894
2.3	-22.078	-22.078	-22.078	-22.078	-22.079	-22.081	-22.087	-22.106	-22.157	-22.285	-22.541	-22.922	-23.377
2.4	-21.704	-21.704	-21.704	-21.704	-21.705	-21.707	-21.713	-21.731	-21.779	-21.900	-22.145	-22.518	-22.968
2.5	-21.414	-21.414	-21.414	-21.414	-21.415	-21.416	-21.422	-21.440	-21.487	-21.602	-21.837	-22.202	-22.649
2.6	-21.191	-21.191	-21.191	-21.191	-21.192	-21.194	-21.200	-21.217	-21.262	-21.373	-21.600	-21.958	-22.401
2.7	-21.022	-21.022	-21.022	-21.022	-21.023	-21.025	-21.031	-21.047	-21.092	-21.199	-21.420	-21.772	-22.212
2.8	-20.897	-20.897	-20.897	-20.897	-20.897	-20.899	-20.905	-20.922	-20.966	-21.070	-21.285	-21.631	-22.068
2.9	-20.806	-20.806	-20.806	-20.806	-20.807	-20.809	-20.814	-20.831	-20.874	-20.976	-21.186	-21.527	-21.961
3.0	-20.744	-20.744	-20.744	-20.744	-20.745	-20.746	-20.752	-20.768	-20.810	-20.910	-21.114	-21.450	-21.881
3.1	-20.704	-20.704	-20.704	-20.704	-20.705	-20.707	-20.712	-20.727	-20.769	-20.866	-21.064	-21.394	-21.821
3.2	-20.683	-20.683	-20.683	-20.683	-20.683	-20.685	-20.690	-20.705	-20.745	-20.839	-21.031	-21.354	-21.778
3.3	-20.675	-20.675	-20.675	-20.676	-20.676	-20.678	-20.682	-20.697	-20.735	-20.825	-21.011	-21.327	-21.745
3.4	-20.680	-20.680	-20.680	-20.680	-20.681	-20.682	-20.686	-20.700	-20.736	-20.823	-21.002	-21.309	-21.722
3.5	-20.693	-20.694	-20.694	-20.694	-20.694	-20.695	-20.700	-20.712	-20.746	-20.829	-21.000	-21.297	-21.704
3.6	-20.713	-20.713	-20.713	-20.713	-20.713	-20.715	-20.718	-20.730	-20.762	-20.839	-21.001	-21.286	-21.676
3.7	-20.729	-20.729	-20.729	-20.729	-20.729	-20.730	-20.734	-20.744	-20.773	-20.843	-20.991	-21.248	-21.589
3.8	-20.718	-20.718	-20.718	-20.718	-20.719	-20.719	-20.722	-20.731	-20.755	-20.813	-20.934	-21.135	-21.375
3.9	-20.650	-20.650	-20.650	-20.650	-20.650	-20.651	-20.653	-20.659	-20.676	-20.717	-20.800	-20.928	-21.071
4.0	-20.519	-20.519	-20.519	-20.519	-20.519	-20.519	-20.521	-20.524	-20.535	-20.560	-20.609	-20.683	-20.767
4.1	-20.358	-20.358	-20.358	-20.358	-20.358	-20.358	-20.359	-20.361	-20.367	-20.381	-20.410	-20.453	-20.508
4.2	-20.202	-20.202	-20.202	-20.202	-20.202	-20.202	-20.203	-20.204	-20.207	-20.216	-20.233	-20.261	-20.301
4.3	-20.069	-20.069	-20.069	-20.069	-20.069	-20.069	-20.069	-20.070	-20.072	-20.078	-20.089	-20.109	-20.141
4.4	-19.963	-19.963	-19.963	-19.963	-19.963	-19.963	-19.963	-19.964	-19.965	-19.969	-19.977	-19.992	-20.019
4.5	-19.883	-19.883	-19.883	-19.883	-19.883	-19.883	-19.883	-19.883	-19.884	-19.887	-19.893	-19.906	-19.929
4.6	-19.825	-19.825	-19.825	-19.825	-19.825	-19.825	-19.825	-19.825	-19.826	-19.829	-19.834	-19.844	-19.865
4.7	-19.787	-19.787	-19.787	-19.787	-19.787	-19.787	-19.787	-19.787	-19.788	-19.790	-19.794	-19.803	-19.821
4.8	-19.765	-19.765	-19.765	-19.765	-19.765	-19.765	-19.765	-19.765	-19.766	-19.767	-19.771	-19.779	-19.795
4.9	-19.756	-19.756	-19.756	-19.756	-19.756	-19.756	-19.756	-19.756	-19.757	-19.758	-19.762	-19.769	-19.784
5.0	-19.759	-19.759	-19.759	-19.759	-19.759	-19.759	-19.759	-19.759	-19.760	-19.761	-19.764	-19.770	-19.784
5.1	-19.771	-19.771	-19.771	-19.771	-19.771	-19.771	-19.771	-19.771	-19.771	-19.772	-19.775	-19.781	-19.793
5.2	-19.790	-19.790	-19.790	-19.790	-19.790	-19.790	-19.790	-19.790	-19.790	-19.791	-19.794	-19.799	-19.811
5.3	-19.815	-19.815	-19.815	-19.815	-19.815	-19.815	-19.815	-19.815	-19.816	-19.817	-19.819	-19.824	-19.834
5.4	-19.846	-19.846	-19.846	-19.846	-19.846	-19.846	-19.846	-19.846	-19.846	-19.847	-19.849	-19.853	-19.863
5.5	-19.880	-19.880	-19.880	-19.880	-19.880	-19.880	-19.880	-19.880	-19.880	-19.881	-19.883	-19.887	-19.895
5.6	-19.917	-19.917	-19.917	-19.917	-19.917	-19.917	-19.917	-19.917	-19.918	-19.918	-19.920	-19.923	-19.931
5.7	-19.957	-19.957	-19.957	-19.957	-19.957	-19.957	-19.957	-19.957	-19.957	-19.958	-19.959	-19.963	-19.970
5.8	-19.999	-19.999	-19.999	-19.999	-19.999	-19.999	-19.999	-19.999	-19.999	-20.000	-20.001	-20.004	-20.011
5.9	-20.043	-20.043	-20.043	-20.043	-20.043	-20.043	-20.043	-20.043	-20.043	-20.043	-20.045	-20.047	-20.054
6.0	-20.088	-20.088	-20.088	-20.088	-20.088	-20.088	-20.088	-20.088	-20.088	-20.088	-20.089	-20.092	-20.098

Table 9. Ne IV cooling

3.5	-26.507	-26.507	-26.507	-26.507	-26.508	-26.510	-26.518	-26.538	-26.580	-26.660	-26.817	-27.100	-27.499
3.6	-24.880	-24.880	-24.881	-24.881	-24.882	-24.884	-24.891	-24.909	-24.948	-25.023	-25.169	-25.438	-25.826
3.7	-23.599	-23.599	-23.599	-23.599	-23.600	-23.602	-23.608	-23.624	-23.661	-23.730	-23.866	-24.120	-24.491
3.8	-22.590	-22.590	-22.590	-22.590	-22.591	-22.593	-22.598	-22.613	-22.647	-22.711	-22.836	-23.070	-23.414
3.9	-21.797	-21.797	-21.797	-21.797	-21.798	-21.799	-21.804	-21.818	-21.848	-21.907	-22.020	-22.230	-22.532
4.0	-21.174	-21.174	-21.174	-21.174	-21.175	-21.176	-21.180	-21.192	-21.220	-21.273	-21.372	-21.554	-21.805
4.1	-20.685	-20.685	-20.685	-20.686	-20.686	-20.687	-20.691	-20.701	-20.726	-20.773	-20.859	-21.011	-21.210
4.2	-20.302	-20.302	-20.302	-20.303	-20.303	-20.304	-20.307	-20.316	-20.338	-20.380	-20.453	-20.579	-20.735
4.3	-20.004	-20.004	-20.004	-20.004	-20.004	-20.005	-20.008	-20.016	-20.036	-20.073	-20.138	-20.243	-20.367
4.4	-19.772	-19.772	-19.772	-19.773	-19.773	-19.774	-19.776	-19.784	-19.802	-19.837	-19.896	-19.988	-20.092
4.5	-19.596	-19.596	-19.596	-19.596	-19.596	-19.597	-19.599	-19.607	-19.625	-19.659	-19.714	-19.798	-19.890
4.6	-19.463	-19.463	-19.463	-19.463	-19.463	-19.464	-19.467	-19.474	-19.492	-19.527	-19.581	-19.661	-19.748
4.7	-19.366	-19.366	-19.366	-19.366	-19.366	-19.367	-19.369	-19.377	-19.396	-19.431	-19.487	-19.565	-19.649
4.8	-19.298	-19.298	-19.298	-19.298	-19.298	-19.299	-19.301	-19.309	-19.328	-19.365	-19.422	-19.500	-19.584
4.9	-19.253	-19.253	-19.253	-19.253	-19.253	-19.254	-19.257	-19.264	-19.284	-19.322	-19.380	-19.459	-19.543
5.0	-19.227	-19.227	-19.227	-19.227	-19.228	-19.228	-19.231	-19.238	-19.258	-19.297	-19.356	-19.436	-19.521
5.1	-19.217	-19.217	-19.217	-19.217	-19.217	-19.218	-19.220	-19.228	-19.247	-19.287	-19.347	-19.427	-19.514
5.2	-19.218	-19.218	-19.218	-19.218	-19.219	-19.219	-19.222	-19.229	-19.248	-19.287	-19.348	-19.428	-19.516
5.3	-19.230	-19.230	-19.230	-19.230	-19.230	-19.231	-19.233	-19.240	-19.258	-19.297	-19.358	-19.438	-19.527
5.4	-19.249	-19.249	-19.249	-19.249	-19.249	-19.250	-19.252	-19.258	-19.276	-19.314	-19.374	-19.454	-19.545
5.5	-19.274	-19.274	-19.274	-19.274	-19.275	-19.275	-19.277	-19.283	-19.300	-19.337	-19.396	-19.475	-19.567
5.6	-19.305	-19.305	-19.305	-19.305	-19.305	-19.306	-19.308	-19.313	-19.329	-19.364	-19.423	-19.501	-19.593
5.7	-19.339	-19.339	-19.339	-19.339	-19.340	-19.340	-19.342	-19.347	-19.361	-19.395	-19.452	-19.529	-19.621
5.8	-19.377	-19.377	-19.377	-19.377	-19.377	-19.378	-19.379	-19.384	-19.397	-19.429	-19.485	-19.561	-19.652
5.9	-19.417	-19.417	-19.417	-19.417	-19.417	-19.418	-19.419	-19.423	-19.436	-19.466	-19.520	-19.594	-19.685
6.0	-19.459	-19.459	-19.459	-19.459	-19.460	-19.460	-19.461	-19.465	-19.476	-19.504	-19.557	-19.629	-19.720

Table 10. Ne V cooling

2.0	-20.926	-20.928	-20.932	-20.945	-20.984	-21.089	-21.313	-21.670	-22.113	-22.593	-23.086	-23.584	-24.084
2.1	-20.478	-20.479	-20.483	-20.494	-20.527	-20.618	-20.822	-21.161	-21.594	-22.071	-22.564	-23.061	-23.560
2.2	-20.136	-20.137	-20.140	-20.149	-20.178	-20.258	-20.443	-20.766	-21.191	-21.664	-22.155	-22.652	-23.151
2.3	-19.871	-19.872	-19.874	-19.883	-19.908	-19.979	-20.149	-20.457	-20.874	-21.344	-21.834	-22.330	-22.829
2.4	-19.659	-19.659	-19.662	-19.669	-19.691	-19.754	-19.911	-20.206	-20.615	-21.082	-21.571	-22.067	-22.566
2.5	-19.480	-19.481	-19.483	-19.489	-19.508	-19.564	-19.709	-19.990	-20.392	-20.855	-21.344	-21.840	-22.338
2.6	-19.327	-19.327	-19.329	-19.335	-19.352	-19.402	-19.535	-19.804	-20.197	-20.658	-21.145	-21.641	-22.139
2.7	-19.199	-19.199	-19.201	-19.206	-19.221	-19.268	-19.392	-19.649	-20.034	-20.491	-20.977	-21.472	-21.971
2.8	-19.099	-19.099	-19.100	-19.105	-19.120	-19.164	-19.281	-19.528	-19.905	-20.358	-20.842	-21.337	-21.836
2.9	-19.027	-19.028	-19.029	-19.034	-19.048	-19.090	-19.203	-19.440	-19.808	-20.257	-20.739	-21.233	-21.731
3.0	-18.984	-18.984	-18.985	-18.990	-19.004	-19.045	-19.153	-19.380	-19.738	-20.181	-20.662	-21.155	-21.653
3.1	-18.965	-18.965	-18.967	-18.971	-18.984	-19.024	-19.127	-19.344	-19.691	-20.127	-20.605	-21.097	-21.595
3.2	-18.967	-18.968	-18.969	-18.973	-18.986	-19.024	-19.121	-19.327	-19.660	-20.089	-20.563	-21.054	-21.552
3.3	-18.988	-18.988	-18.990	-18.993	-19.005	-19.040	-19.131	-19.324	-19.644	-20.062	-20.532	-21.022	-21.519
3.4	-19.023	-19.024	-19.025	-19.028	-19.039	-19.071	-19.154	-19.334	-19.638	-20.046	-20.511	-20.999	-21.495
3.5	-19.071	-19.071	-19.072	-19.075	-19.085	-19.113	-19.189	-19.355	-19.641	-20.036	-20.495	-20.981	-21.477
3.6	-19.128	-19.128	-19.129	-19.132	-19.140	-19.165	-19.233	-19.385	-19.653	-20.033	-20.485	-20.967	-21.459
3.7	-19.193	-19.193	-19.194	-19.196	-19.203	-19.225	-19.285	-19.422	-19.671	-20.035	-20.476	-20.948	-21.419
3.8	-19.263	-19.263	-19.264	-19.266	-19.272	-19.290	-19.342	-19.465	-19.694	-20.036	-20.457	-20.895	-21.291
3.9	-19.335	-19.335	-19.336	-19.338	-19.343	-19.358	-19.402	-19.509	-19.715	-20.029	-20.407	-20.766	-21.035
4.0	-19.403	-19.403	-19.404	-19.405	-19.409	-19.422	-19.458	-19.549	-19.727	-19.998	-20.307	-20.561	-20.718
4.1	-19.458	-19.459	-19.459	-19.460	-19.463	-19.473	-19.502	-19.574	-19.720	-19.936	-20.166	-20.329	-20.422
4.2	-19.492	-19.492	-19.492	-19.493	-19.495	-19.502	-19.524	-19.578	-19.689	-19.849	-20.008	-20.112	-20.172
4.3	-19.498	-19.498	-19.498	-19.499	-19.500	-19.505	-19.520	-19.558	-19.636	-19.749	-19.856	-19.924	-19.967
4.4	-19.477	-19.477	-19.477	-19.477	-19.479	-19.482	-19.491	-19.516	-19.569	-19.644	-19.716	-19.763	-19.794
4.5	-19.431	-19.431	-19.431	-19.431	-19.432	-19.434	-19.440	-19.455	-19.489	-19.538	-19.586	-19.619	-19.643
4.6	-19.359	-19.359	-19.359	-19.359	-19.360	-19.361	-19.364	-19.373	-19.394	-19.425	-19.457	-19.479	-19.498
4.7	-19.255	-19.255	-19.255	-19.255	-19.256	-19.256	-19.258	-19.263	-19.275	-19.293	-19.313	-19.329	-19.342
4.8	-19.116	-19.116	-19.116	-19.116	-19.116	-19.117	-19.118	-19.120	-19.127	-19.137	-19.149	-19.159	-19.168
4.9	-18.954	-18.954	-18.954	-18.954	-18.954	-18.954	-18.954	-18.956	-18.959	-18.965	-18.971	-18.977	-18.983
5.0	-18.788	-18.788	-18.788	-18.788	-18.788	-18.788	-18.788	-18.789	-18.790	-18.794	-18.797	-18.801	-18.805
5.1	-18.635	-18.635	-18.635	-18.635	-18.635	-18.636	-18.636	-18.636	-18.637	-18.639	-18.641	-18.643	-18.646
5.2	-18.505	-18.505	-18.505	-18.505	-18.505	-18.505	-18.505	-18.505	-18.506	-18.507	-18.508	-18.510	-18.512
5.3	-18.399	-18.399	-18.399	-18.399	-18.399	-18.399	-18.399	-18.399	-18.400	-18.400	-18.401	-18.402	-18.404
5.4	-18.316	-18.316	-18.316	-18.316	-18.316	-18.316	-18.316	-18.316	-18.317	-18.317	-18.318	-18.319	-18.320
5.5	-18.254	-18.254	-18.254	-18.254	-18.254	-18.254	-18.254	-18.254	-18.254	-18.254	-18.255	-18.256	-18.256
5.6	-18.209	-18.209	-18.209	-18.209	-18.209	-18.209	-18.209	-18.209	-18.209	-18.209	-18.210	-18.210	-18.211
5.7	-18.179	-18.179	-18.179	-18.179	-18.179	-18.179	-18.179	-18.179	-18.179	-18.179	-18.179	-18.180	-18.180
5.8	-18.161	-18.161	-18.161	-18.161	-18.161	-18.161	-18.161	-18.161	-18.161	-18.161	-18.161	-18.161	-18.162
5.9	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.153	-18.153
6.0	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.152	-18.153

Table 11. Cooling from other ions

	H I	H II	C IV	O V
3.5	-33.939	-22.684	-29.877	-48.346
3.6	-30.636	-22.752	-27.297	-30.612
3.7	-28.019	-22.820	-25.257	-28.029
3.8	-25.946	-22.887	-23.646	-25.991
3.9	-24.305	-22.954	-22.375	-24.386
4.0	-23.009	-23.020	-21.374	-23.125
4.1	-21.985	-23.085	-20.588	-22.136
4.2	-21.177	-23.149	-19.973	-21.362
4.3	-20.542	-23.212	-19.494	-20.753
4.4	-20.044	-23.274	-19.122	-20.262
4.5	-19.654	-23.334	-18.836	-19.849
4.6	-19.351	-23.393	-18.617	-19.487
4.7	-19.116	-23.450	-18.453	-19.169
4.8	-18.936	-23.505	-18.331	-18.897
4.9	-18.799	-23.559	-18.244	-18.673
5.0	-18.696	-23.610	-18.183	-18.495
5.1	-18.621	-23.660	-18.144	-18.357
5.2	-18.567	-23.708	-18.123	-18.253
5.3	-18.531	-23.754	-18.114	-18.178
5.4	-18.508	-23.799	-18.117	-18.127
5.5	-18.496	-23.843	-18.128	-18.095
5.6	-18.493	-23.887	-18.145	-18.078
5.7	-18.496	-23.929	-18.169	-18.073
5.8	-18.505	-23.970	-18.196	-18.079
5.9	-18.518	-24.009	-18.227	-18.092
6.0	-18.535	-24.044	-18.260	-18.112

REFERENCES

Aggarwal, K. M. 1983, MNRAS, 202, 15p

Aggarwal, K. M. 1993, ApJS, 85, 197

Aggarwal, K. M., Berrington, K. A., Eissner, W., & Kingston, A. E. 1986, Recommended Data from the Daresbury Atomic Data Workshop 1985 (Belfast: Daresbury Atomic Data Bank)

Allard, N., Artru, M.-C., Lanz, T., & Le Dourneuf, M. 1990, A&AS, 84, 563

Arnaud, M., & Rothenflug, R. 1985, A&AS, 60, 425

Badnell, N. R. 1987, J. Phys. B, 20, 2081

Badnell, N. R. 1991, ApJ, 379, 356

Badnell, N. R., & Pindzola, M. S. 1989, Phys. Rev. A, 39, 1690

Balick, B., Mellema, G., & Frank, A. 1993, A&A, 275, 588

Biémont, E., Delahaye, F., & Zeippen, C. J. 1994, J. Phys. B, 27, 5841

Biro, S., Raga, A. C., & Cantó, J. 1995, MNRAS, 275, 557

Blondin, J. M., Königl, A., & Fryxell, B. 1989, ApJ, 337, L37

Blondin, J. M., Fryxell, B., & Königl, A. 1990, ApJ, 360, 370

Brage, T., Froese-Fischer, C., & Judge, P. G. 1995, ApJ, 445, 457

Cai, W., & Pradhan, A. K. 1993, ApJS, 88, 329

Chernin, L., Masson, C., Gouveia dal Pino, E. M., & Benz, W. 1994, ApJ, 426, 204

Choe, S. U., Böhm, K. H., & Solf, J. 1985, ApJ, 288, 338

Chung, S., Lin, C. C., & Lee, E. T. P. 1991, Phys. Rev. A, 43, 3433

Cox, D. P. 1970, Ph.D. thesis, Univ. California, San Diego

Dgani, R., Van Buren, D., & Noriega-Crespo, A. 1996, ApJ, 461, 927

Falle, S. A. E. G. 1981, MNRAS, 195, 1011

Falle, S. A. E. G., & Raga, A. C. 1993, MNRAS, 261, 573

Falle, S. A. E. G., & Raga, A. C. 1995, MNRAS, 272, 785

Ferland, G., Binette, L. Contini, M., Harrington, J., Kallman, T., Netzer, H., Péquignot, D., Raymond, J., Rubin, R., Shields, G., Sutherland, R., & Viegas, S. 1995, in The Analysis of Emission Lines, ed. R. Williams & M. Livio (Cambridge:CUP), p. 83

Fleming, J., Bell, K. I., Hibbert, A., Vaeck, N., & Godefroid, M. R. 1996, MNRAS, 279, 1289

Frank, A., & Mellema, G. 1994a, A&A, 289, 937

Frank, A., & Mellema, G. 1994b, ApJ, 430, 800

Gaetz, T. J., & Salpeter E. E. 1983, ApJS, 52, 155

Gallagher, J. W., & Pradhan, A. K. 1985, JILA Information Center Report No. 30, Boulder

Gouveia dal Pino, E. M., & Benz, W. 1993, ApJ, 410, 686

Gouveia dal Pino, E. M., & Benz, W. 1994, ApJ, 435, 261

Hartigan, P., Raymond, J. C., & Hartmann, L. 1987, ApJ, 316, 323

Hartigan, P., Raymond, J. C., & Meaburn, J. 1990, ApJ, 362, 624

Hartmann, L., & Raymond, J. C. 1984, ApJ, 276, 560

Innes, D. 1985, Ph.D. thesis, Univ. College, London

Kafatos, M. 1973, ApJ, 182, 433

Keenan, F. P., Feibelman, W. A., & Berrington, K. A. 1992, ApJ, 389, 443

Keenan, F. P., Hibbert, A., Ojha, P. C., & Conlon, E. S. 1993, Phys. Scr., 48, 129

Kingdon, J. B., & Ferland, G. J. 1996, ApJS, 106, 205

Landini, M., & Monsignori Fossi, B. C. 1990, A&AS, 82, 229

Lotz, W. 1967, ApJS, 14, 207

Lundqvist, P., & Fransson, C. 1991, ApJ, 380, 575

Lundqvist, P., & Fransson, C. 1996, ApJ, 464, 924

Lundqvist, P., et al. 1996, in preparation

McLaughlin, B. M., & Bell, K. L. 1993, J. Phys. B, 26, 1797

Mellema, G. 1995, MNRAS, 277, 173

Mellema, G., & Frank, A. 1995, MNRAS, 273, 401

Mendoza, C. 1983, IAU Symp. 103, Planetary Nebulae, ed. D. R. Flower (Dordrecht:Reidel), 143

Nahar, S. N. 1995, ApJS, 101, 423

Nussbaumer, H., & Storey, P. 1983, A&A, 126, 75

Nussbaumer, H., & Storey, P. 1987, A&AS, 69, 123

Osterbrock, D. A. 1989, Astrophysics of Gaseous Nebulae and Active Galactive Nuclei (Mill Valley,CA:University Science Books)

Peng, J. F., & Pradhan, A. K. 1995, ApJS, 112, 151

Péquignot, D. 1986, Editor, Workshop on Model Nebulae, Puclication de l'Observatoire de Paris

Raga, A. C. 1988, ApJ, 335, 820

Raga, A. C. 1989, in Proceedings of the ESO Workshop on Low Mass Star Formation and Pre-Main Sequence Objects, ed. B. Reipurth (Garching:ESO), p. 281

Raga, A. C. 1994, in Stellar and Circumstellar Astrophysics, ed. G. Wallerstein & A. Noriega-Crespo, P.A.S.P. Conf. Proc., Vol. 57, p. 85

Raga, A. C., & Böhm, K. H. 1985, ApJS, 58, 201

Raga, A. C., & Böhm, K. H. 1986, ApJ, 308, 829

Raga, A. C., & Böhm, K. H. 1987, ApJ, 323, 193

Raga, A. C., Mateo, M., Böhm, K. H., & Solf, J. 1988, AJ, 95, 1783

Raga, A. C., Taylor, S. D., Cabrit, S., & Biro, S. 1995, A&A, 296, 833

Raymond, J. C. 1979, ApJS, 39, 1

Różyczka, M., & Tenorio-Tagle, G. 1985, A&A, 147, 220

Seaton, M. J. 1959, MNRAS, 119, 81

Shull, J. M., & McKee, C. F. 1979, ApJ, 227, 131

Stafford, R. P., Bell, K. L., Hibbert, A., & Wijesundera, W. P., 1994, MNRAS, 268, 816

Stone, J. M., & Norman, M. L. 1993a, ApJ, 413, 210

Stone, J. M., & Norman, M. L. 1993b, ApJ, 413, 198

Stone, J. M., & Norman, M. L. 1994a, ApJ, 420, 237

Stone, J. M., & Norman, M. L. 1994b, ApJ, 422, 348

Zhang, H. L., Graziani, M., & Pradhan, A. K. 1994, A&A, 283, 319

This preprint was prepared with the AAS LaTeX macros v4.0.